A NEW CONSIDERATION FOR THE COUPLED OCEAN-ACOUSTIC MODELING

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ABSTRACT: Based on the review of the computational ocean acoustic propagation modeling, the paper put forward a new consideration for the coupled ocean-acoustic modeling from the perspective of energy transfer. In respect that the classical models of acoustic propagation just regard the variation of the seawater as the force term which is sometimes experimental and have to discuss various situations when the ocean is dynamically complex or unclear, the new consideration makes use of the coupled ocean-acoustic modeling and a recent method in ocean dynamics study – multiscale energy and vorticity analysis (MS-EVA). In MS-EVA, the energy transfer can be calculated which called "canonical transfer". After applying canonical transfer to couple the conversion of the acoustic energy and the energy of seawater such as kinetic energy, the energy transfer can be utilized to amend the initial acoustic propagation. This new consideration has many advantages as well as some difficulties to carry out. If it comes true, it makes sense for acoustic propagation modeling in complex or even unclear dynamics ocean.

Keywords: Acoustic propagation, coupled ocean-acoustic modeling, canonical transfer, underwater acoustics.

INTRODUCTION

The acoustic propagation in the sea has been studied intensely since the beginning of Second World War when it was recognized that an understanding of this phenomenon was essential to the successful conduct of anti-submarine warfare operations. The study of acoustic propagation in the sea is fundamental to the understanding and prediction of all other underwater acoustic phenomena. The essentiality of propagation models is inherent in the hierarchy of ocean acoustic models.

There are 30 or more models to compute the ocean acoustic propagation field. The basic consideration of the models is the effect of the temporal and spatial variation of the ocean environment such as sea surface and sea floor, fronts and eddies, internal waves and so on. The differences are just the domains of applicability, operational speed and computational accuracy. The theoretical basis underlying all mathematical models of acoustic propagation is the wave equation. However, the variation of the sea water is just regarded as the force term which is sometimes experimental. More important, when the ocean environment is dynamically complex or unclear, the classical models have to discuss various situations.

Recently, in the ocean dynamics study, Liang and Robinson proposed a new method – multiscale energy and vorticity analysis (MS-EVA), to investigate the complex nonlinear oceanic processes. It is real problem–oriented and is objective in nature. Through exploring pattern generation and energy and enstrophy transfers, transports, and conversions, it helps to unravel the intricate relationships between events on different scales and locations in phase and physical spaces. In view that the acoustic propagation is in fact the propagation of the sound energy, we can consider the energy transfer between sound and the ocean. If we knew this energy transfer, then we can derive the propagation of the sound energy from the ocean parameters. In MS-EVA, the energy transfer can be calculated which called "canonical transfer" in distinction to those transfers one might have encountered in the literature. From this point, a new consideration of acoustic propagation related to MS-EVA can be put forward. In the framework of MS-EVA, a function space is decomposed into a direct sum of several mutually orthogonal subspaces, each termed a scale window. Since the bound of the scale window is determined by man and the scales can be not only spatial but also temporal, the new consideration is very useful to investigate the acoustic propagation in complex or even uncertain dynamics ocean such as ocean with mesoscale phenomena. In this paper, we will review the former researches and show the advantages of the new consideration.

The paper is organized as follows. The researches of acoustic propagation in ocean environment with mesoscale phenomena are briefly reviewed in section 2. After the MS-EVA and canonical transfer are introduced in section 3, the new consideration and its advantages are present in section 4. In section 5, we will discuss the disadvantages and other related considerations.

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BRIEF REVIEW OF ACOUSTIC PROPAGATION MODELS IN OCEAN ENVIRONMENT

The ocean is a waveguide, bounded above by a pressure release surface and below by a viscous-elastic medium. The physical oceanographic parameters, as classically represented by the ocean sound speed structure, make up the index of refraction of the water column waveguide. The combination of water column and bottom properties leads to a set of generic sound propagation paths descriptive of most propagation phenomena in the ocean.

Sound propagation in the ocean is mathematically described by the wave equation, whose parameters and boundary conditions are descriptive of the ocean environment. As schematically shown in Fig.1, there are essentially five types of models (computer solutions to the wave equation) to describe sound propagation in the sea: Spectral or "fast field program" (FFP), normal mode (NM), ray, and parabolic equation (PE) models, and direct finite-difference (FD) or finite-element (FE) solutions of the full wave equation. All of these models permit the ocean environment to vary with depth. A model that also permits horizontal variations in the environment, i.e., sloping bottom or spatially variable oceanography, is termed range dependent. As shown in Fig.1, an a priori assumption about the environment being range independent, leads to solutions based on spectral techniques (FFP) or normal modes (NM); both of these techniques can , however, be extended to treat range dependence. Ray, PE and FD/FE solutions are applied directly to range varying environments. For high frequencies (few kilohertz or above), ray theory, the infinite frequency approximation, is still the most practical, whereas the other four model types become more and more applicable below, say, a kilohertz.

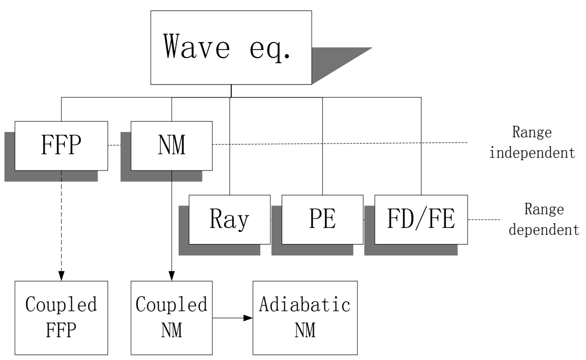

Fig.1 Hierarchy of ocean acoustic propagation models

All of the classical models attempt to describe reality and to solve the Helmholtz equation in one way or another. They therefore should be consistent, and there is much insight to be gained from understanding this consistency. The models ultimately compute propagation loss, which is taken as the decibel ratio of the pressure at the field point to a reference pressure, typically 1m from the source.

In the classical models, the physical oceanographic parameters are ultimately represented by the ocean sound speed structure. However, the precise sound speed structure is very difficult to achieve so many results appear and are almost experimental. Can we avoid this difficulty instead of other ways? For example, in the initial acoustic propagation model the features of ocean environment or the sound speed do not change, and after some operations the initial acoustic propagation can be amended with the variation of the ocean. Herein the operations relate to an energy transfer ---- the canonical transfer.

CANONICAL TRANSFER AND MULTISCALE ENERGY AND VORTICITY ANALYSIS

The new consideration has much to do with the multiscale energy and vorticity analysis. In this part, the MS-EVA method is introduced. The MS-EVA is a new methodology for the investigation of multiscale interactive oceanic processes that are intermittent in space and time. The basic idea is delineated and the formulation is developed in Liang and Robinson (2005, hereinafter LR1), and an avenue to application is established in Liang and Robinson (2007, hereinafter LR2). Also established in LR2 is a generalization of the concept of stability on a localized basis, which allows one to build an easy-to-use criterion for the identification of baroclinic and barotropic instability processes for real ocean and atmosphere datasets.

In the MS-EVA, processes are represented on scale windows. By a *scale window* we mean a subspace of the space to which the field under consideration belongs, with a certain range of scales involved. The range is delimited by scales in the spirit of orthonormal wavelet analysis and is expressed in scale levels (cf. LR1; Kumar and Foufoula-Georgiou 1997). A scale level j is a dimensionless index such that 2^{-j} measures the passage of events since the beginning for a time series scaled by its duration. For the IFF process, we particularly need three scale levels, j_0, j_1, and j_2, $j_0 \le j_1 \le j_2$, that demarcate three mutually exclusive windows: 1) large-scale window ($j \le j_0$); 2) mesoscale window ($j_0 < j \le j_1$); and 3) submesoscale window ($j_1 < j \le j_2$). For simplicity, a window may be referenced as ϖ, with ϖ = 0, 1, 2 standing for large scale, mesoscale, and submesoscale, respectively. The MS-EVA provides a way to study the interactions between these windows.

We can use the multiscale energetics of the MS-EVA for the acoustic propagation study. For convenience, we use kinetic energy to represent the energy of seawater and beam conversion to denote the conversion from acoustic energy of sound beam to kinetic energy. In a symbolic form, the growths of kinetic energy (K_n^{ϖ}) and acoustic energy (A_n^{ϖ}) on window ϖ (ϖ = 0, 1, 2) and at time step *n* for a frictionless fluid flow are governed by

$$\dot{K}_n^{\varpi} = \Delta Q_{K_n^{\varpi}} + T_{K_n^{\varpi}} + c_n^{\varpi} + B_{K_n^{\varpi}} \tag{1}$$

$$\dot{A}_n^{\varpi} = \Delta Q_{A_n^{\varpi}} + T_{A_n^{\varpi}} - c_n^{\varpi} + B_{A_n^{\varpi}} \tag{2}$$

Where $\dot{K}_n^{\varpi}$ denotes the time rate of change of KE, and the B terms indicate the effect of the boundary, and the ΔQ terms represent transport processes in physical space, and the ''*T* terms''

$$T_{K_n^{\varpi}} = T_{K_n^{\varpi},h} + T_{K_n^{\varpi},z} + TS_{K_n^{\varpi}} \tag{3}$$

$$T_{A_n^{\varpi}} = T_{A_n^{\varpi},h} + T_{A_n^{\varpi},z} \tag{4}$$

are *canonical transfers* among scale windows in the sense that they vanish when averaged over windows ϖ and time steps *n.* In the equations, the symbol $(\bullet)_n$ indicates a multiscale window transform (LR1, section 2) on time window ϖ and at times *n.*

The localized energetics in Eqs. (3) and (4) can be better understood with the aid of a schematic. Figure 2 presents the energy flow for the case of a two-window decomposition (window 0 and window 1), a simplified version of the three-window case (cf. Fig. 7 of LR1). From it one sees that beam conversion always occurs within the same window, and the interplay between windows is through the *T* terms or perfect transfers. Note that there are no window indices assigned to T_K and T_A in the schematic, as they bridge two different scale windows. They should be understood as $T_{K_n^0}$ and $T_{A_n^0}$ if the large-scale energetics are considered, while in the mesoscale energy balance they are $T_{K_n^1}$ and $T_{A_n^1}$, respectively.

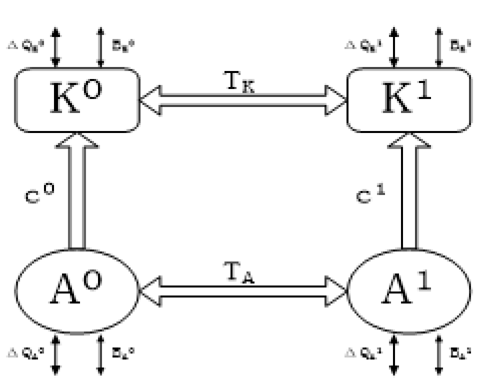

Fig. 2. A schematic of the energetics for a two-window decomposition. The symbols are the same as those in (1) and (2), except that the subscript n (time step) is omitted for simplicity. The windows 0 and 1 should be understood as, respectively, the large scale window and mesoscale window. The conversion is just from AE to KE.

Canonical transfer is a key concept in the MS-EVA formulation (LR1). It allows one to separate transport processes from the nonlinear energetics terms based on a firm physical ground and, hence, to tell whether the energy growth for a window at a particular location and time is due to the local energy transfer or transport from surrounding regions. A natural generalization of these stability theories to handle real world problems is fulfilled with these terms. All the above terms are local in time and space, and hence the criterion is applicable to problems on a generic basis.

Technology of the new consideration

The new consideration is similar to the previous coupled ocean-acoustic modeling. The general coupled ocean-acoustic forecast systems comprise three basic components: an oceanic forecast scheme, a coupling scheme and an ocean acoustic propagation scheme (Robinson *et al.,* 1994). These systems can also be used to generate nowcasts and hindcasts. Nowcasts are estimates of the present state of a system. They are based on a combination of observations and dynamical modeling. Hindcasts are *a posteriori* forecasts. They are useful in evaluating modeling capabilities based on historical benchmark data (e.g. Martin, 1993). Requirements for oceanographic data to support coupled ocean-acoustic forecast systems often exceed observational capabilities. Therefore, data assimilation, which introduces data generated by feature models, is used to achieve accurate synoptic realizations. Feature models are statistical representations of common synoptic structures in the ocean such as fronts and eddies (Robinson *et al., 1994).*

However, in the former coupled ocean-acoustic system, the acoustic models were various to adapt different oceanic and synoptic structures; besides, the so-called coupling was just the ocean models generating input variables necessary for initialization of the acoustic models and so did not embody the interaction. Can we use only one unified acoustic model but applicable for different oceanic structures and the coupling embody the interaction? The new consideration can do it.

There are four steps to implement the new consideration. The first step which is identical to the former coupled ocean-acoustic system is using ocean models to output oceanic parameters containing different oceanic structures. The second step is employing a simple wave equation in which the features of ocean environment do not change as the initial acoustic propagation model. These two steps can carry out at the same time. After that, the third step is applying canonical transfer in MS-EVA to couple the conversion of the acoustic energy and the energy of seawater such as kinetic energy. This is the key step which determines the quality of the whole system. Then the final step is utilizing the energy transfer to amend the initial acoustic propagation.

In order to realize the consideration, a key technology should be conquered. The key technology of the consideration is how to depict the conversion rate of the acoustic energy and the energy of seawater with mathematical expression of physical quantities. In the previous papers using MS-EVA, the conversion was just buoyancy conversion between kinetic energy and available potential energy and the conversion rate had been used frequently in geophysical fluid dynamics diagnostics. Nevertheless, in this study, the conversion rate is not so easy but once it carries into effect the consideration can bring many advantages.

The advantages of the new consideration are obvious. First of all, in this consideration it is not necessary to discuss various situations about the effect of different ocean dynamical features on acoustic propagation. Furthermore, it is not essential to know the dynamics of oceanic processes if data assimilation is utilized. Therefore, it is applicable for the acoustic propagation in uncertain dynamics oceans such as ocean with mesoscale phenomena. Secondly, in many previous models the impact of ocean was simply parameterized with empirical formula so the application scope was quite limited, whereas this consideration can describe the effect of ocean precisely as long as the mathematical expressions of the conversion are not empirical. Thirdly, the consideration can give full play to advantages of the coupled ocean-acoustic modeling such as generating timely forecasts of sonar performance in the vicinity of highly variable frontal features. Last but not least, the MS-EVA method in the consideration is able to analyze the complex ocean to reveal the dynamical processes and then it can used to evaluate other acoustic propagation models.

Summary and discussion

Based on the review of the computational ocean acoustic propagation modeling, the paper put forward a new consideration from the perspective of energy transfer. In respect that the classical models of acoustic propagation just regard the variation of the seawater as the force term which is sometimes experimental and have to discuss various situations when the ocean is dynamically complex or unclear, the new consideration makes use of the coupled ocean-acoustic modeling and a recent method in ocean dynamics study– multiscale energy and vorticity analysis (MS-EVA). In MS-EVA, the energy transfer can be calculated which called “canonical transfer”. After applying canonical transfer to couple the conversion of the acoustic energy and the energy of seawater such as kinetic energy, the energy transfer can be utilized to amend the initial acoustic propagation. It is obvious to see many advantages in the new consideration.

Of course the new consideration is not all-around. Except the difficulty of conversion rate, the effect of the boundary and the amount of calculation would be other problems. The coupled system needs simultaneous equation so the calculation quantity should be rather large but with the development of the computer it is not difficult to solve. However, the effect of the boundary especially the uncertainty of the boundary is not easy to tackle. Herein we consider another transfer theory which is not mature yet. The theory is about the information transfer between dynamical system components. If we regard the coupling of the ocean and acoustics as a dynamical system, the ocean environment should be one component and the propagating acoustic energy should be another component. If we could quantize the information transfer between the ocean component and the acoustic component, the troubles brought by the uncertainty of the boundary would be overcome. If it comes true, it makes good sense for ocean acoustic propagation modeling.

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